Range Measurements to Pioneer 10 Using the Digitally Controlled Oscillator

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Analysis of the new doppler data from DSS 14 using the Digitally Controlled Oscillator (DCO), has established that ramping the carrier frequency by the DCO will enable us to obtain range measurements to Pioneer 10 without the use of a ranging system per se. The accuracy of these measurements is on the order of 10 km.

I. Introduction

The tuned oscillator range analysis (TORA) experiment utilizes the new DSN programmed oscillator device at DSS 14. This new equipment was added to DSS 14, Goldstone, California, and DSS 43, Canberra, Australia, for the purpose of tracking Pioneer 10 during Jupiter flyby. It was noted that ranging information could be obtained when the transmitted frequency was ramped by means of a digitally controlled oscillator (DCO). The returned signal shows a pattern that is dependent upon the round-trip light time, enabling measurements to be made of the distance from the station to the spacecraft.

Since the primary purpose of the installation of the DCOs was to support Pioneer 10 commanding during Jupiter encounter, training exercises were scheduled to permit station operators to become familiar with the new equipment and to establish working procedures for the Jupiter flyby. Data taken from DSS 14 were utilized during several of these training exercises, and processing of the data was begun to see if range information could be extracted. Supplied with information about the frequency rates and initiation times of the DCO during those passes, the data were successfully analyzed and several round-trip range estimates of the Pioneer 10 spacecraft were made.

The concept of using ramped frequency doppler for ranging is analogous to inferring distances by an echo. By ramping the carrier frequency, a unique correspondence between time of transmission and frequency of transmission is established. Further, by noting the time and frequency of reception, one can then associate a time of transmission with that frequency; thus a time delay, or round-trip distance, is inferred.

Figure 1 is an illustration of this principle. It shows the doppler counter readings after subtraction of reasonable estimates of shifts due to Earth and spacecraft motion, etc., computed as ordinary doppler at the initial transmitted frequency. The dashed line indicates the tuning profile of the exciter at DSS 14 as a function of time. The exciter is also used as a reference signal to heterodyne the time-delayed received signal from Pioneer 10 (effects on residuals shown as a solid line). The difference between the reference frequency and the received signal is interpreted as Pioneer 10 "doppler data," to be used in the orbit determination process. The effects of the ramps on the received signal (solid line) are also shown, but with a delay of about 1 h, which is the time required for the signal to reach the spacecraft and return to the ground. As can be seen, the difference between the received signal and the ground reference produces the doppler residuals, which are on the order of 200 kHz.

II. Data Analysis

Two sets of DSS 14 Pioneer 10 data were analyzed. The ramp patterns are tabulated in Tables 1 and 2. The first pass of data (Pass I) was taken on June 19, 1973, and the second (Pass II) on July 10, 1973.

A. Pass I

To analyze this pass, we used the initial conditions of Pioneer 10, supplied by Pioneer Project Navigation. Based upon this orbit, round-trip light times for each data point were computed. The extra cycles were removed from the data according to the required light time transit.

The result is presented in Fig. 2. It is interesting to note the step residuals due to the misplacement of Pioneer 10 in this assumed trajectory by approximately 250 km. The ramped doppler data provide an additional measurement dimension not readily or directly available from conventional doppler. The unramped doppler yields a solution of the orbit by inference through the acceleration dynamics after sufficient spatial motion has occurred (about 6 weeks or longer).

The step biases are due to a trajectory round-trip light-time error times a ramp rate. Since we may regard the orbit error to be a constant over one pass, the offsets are due only to differing ramp rates. Thus, the largest offset is due to a ramp rate of 150 Hz/s. Halfway between, one sees a bias of half that resulting from a ramp rate of 74.9984 Hz/s. Centered about zero are the two offsets caused by a ramp rate of ± 30 Hz/s.

B. Pass II

A second set of data, taken on July 10, 1973, was analyzed. In the intervening period, a trim maneuver had taken place. This necessitated a solution for the new orbit. Additions were made to the code in the Planetary Orbiter Error Analysis Study (POEAS) program, which included the new data and partial derivatives required for an automatic least-squares differential-correction process. The July 10 data were sent through POEAS, and automatic iterations for the solution of the new orbit were begun. After the first iteration (the best available solution was not used), the Doppler data were centered about zero, but the range was still in error by an amount equivalent to 0.5 Hz (Fig. 3). Since the ramp rates for this pass were all 100 Hz/s at S-band, the offsets were the same size and centered about zero. After the second iteration, all of the biases disappeared, indicating the data derivative formulation and program coding to be correct and thus causing the solution to converge. There was a reported programmed oscillator control assembly (POCA) initiation time error of 5 s, causing residuals of 500 Hz to appear in the middle of this pass. For the sake of this demonstration rather than correcting the time inputs to the program, these data were eliminated from the data set used for the orbit solution.

When the "blunder points" were removed, we were able to adjust the orbit so that the data residuals were on the order of 1/1000 Hz. Figure 4 shows the result of this solution.

The figure shows the level to which the ramp frequency data can be fit when all the blunder points have been removed. It is evident that the only noise component remaining is the high-frequency component, and when the ramp pattern is included in the data analysis, the new DCO doppler data residuals look the same as the conventional unramped data residuals.

III. Conclusions and Summary

Based on the analysis of two sets of Pioneer 10 ramping doppler data from DSS 14, the system shows promise of providing a new measurement dimension (i.e., range) from doppler data. The problems at present seem tractable.

Our interpretation of the data seems sound, and its incorporation into computer programs yielded reasonable results. The prototype program furnishes us with insights into the procedures for developing the navigation programs to account for this new data type in a logical manner.

In summary, as a demonstration exercise, we have

(1) Obtained some understanding of the POCA.

(2) Developed the software required to analyze the data from an orbital correction approach.

(3) Interpreted our results in terms of a new data type corresponding to topocentric range to the spacecraft.

Table 1. Ramp test pattern for June 19, 1973; start time T_0 = 9:40:00

Ramp No.	Ramp on time ($T_0 + T$)			Ramp rate (S-band) at exciter, Hz/s
	n	min	s	
1	0	0	0	150
2	0	3	20	75[a]
3	0	10	00	30
4	1	27	47	0
5	1	32	47	−30
6	2	50	34	−75[a]
7	2	57	14	−150
8	3	00	34	0
9	3	05	47	−150
10	3	09	07	−75[a]
11	3	15	47	−30
12	4	33	34	0
13	4	38	34	30
14	5	56	21	75[a]
15	6	03	01	150
16	6	06	21	0

[a]Actual S-band rate ±74.9984 Hz/s.

Table 2. Ramp test pattern for July 10, 1973

Ramp No.	Ramp on time, GMT			Ramp rate (DCO)[a] at exciter, Hz/s
	n	min	s	
1	06	30	00	3.125
2	06	46	40	0
3	07	09	43	−3.125
4	07	26	23	0
5	07	47	03	−3.125
6	08	03	43	0
7	08	26	46	+3.125
8	08	43	26	0
9	09	04	06	+3.125
10	09	20	46	0
11	09	43	59	−3.125
12	10	00	39[b]	0
13	10	21	19	−3.125
14	10	37	59	0
15	11	01	02	+3.125
16	11	17	42	0
17	11	38	22	+3.125
18	11	55	02	0
19	12	18	04	−3.125
20	12	34	44	0

[a]S-band rate = 32 × DCO rate = 100 Hz/s.
[b]Suspected time error of −5 s.

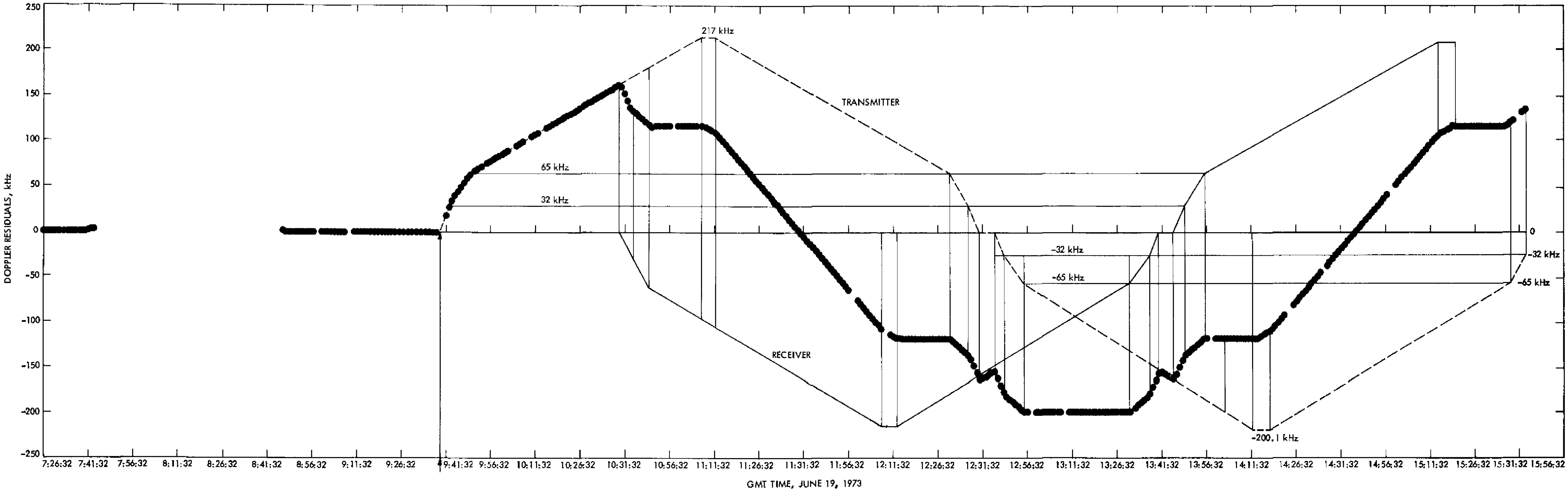

Fig. 1. Tora experiment, June 19, 1973—DSN 14 Pioneer 10 doppler residuals (effects of ramps not modeled)

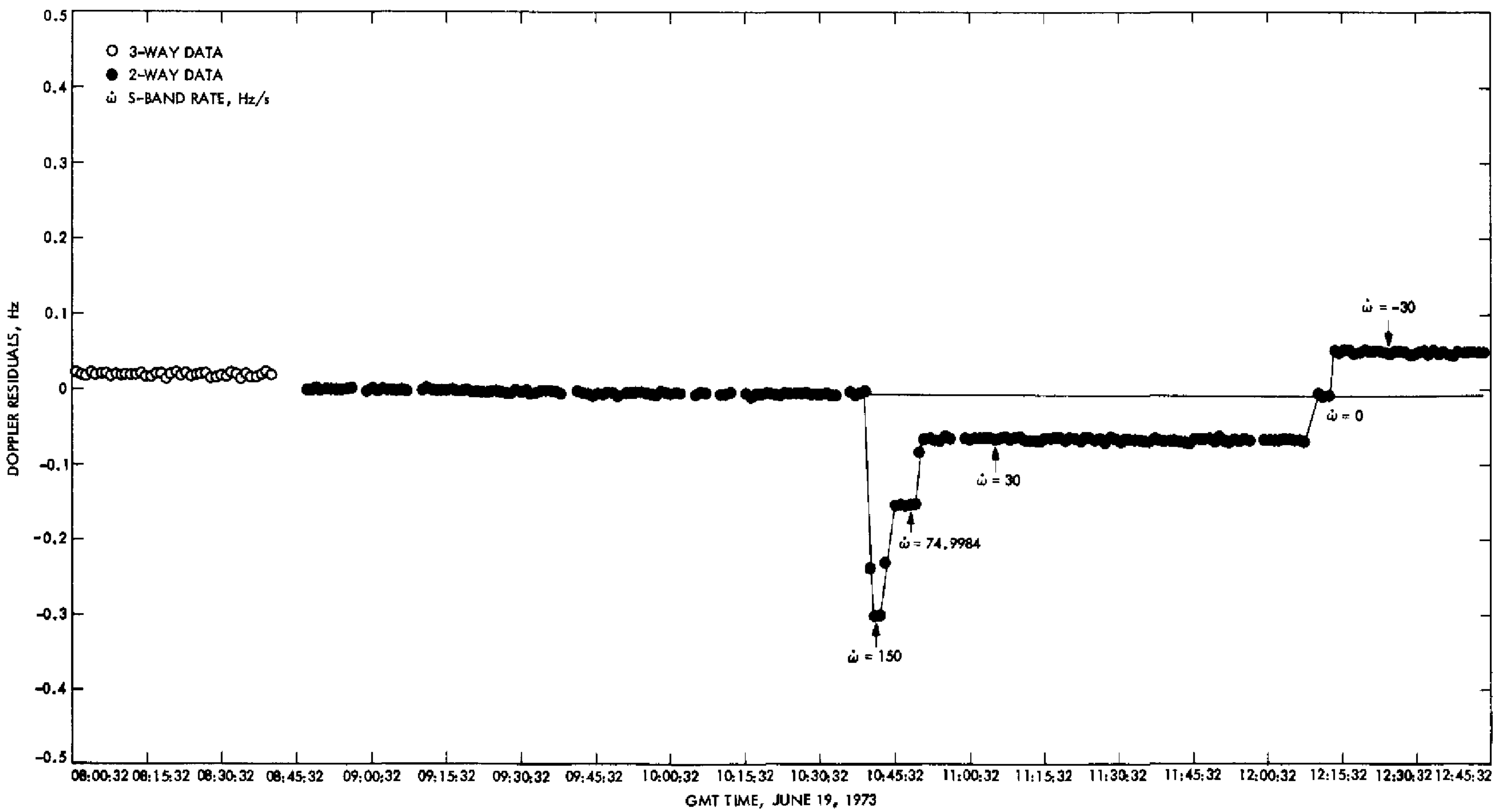

Fig. 2. Tora experiment, June 19, 1973—DSN 14 Pioneer 10 residuals (ramp effects modeled)

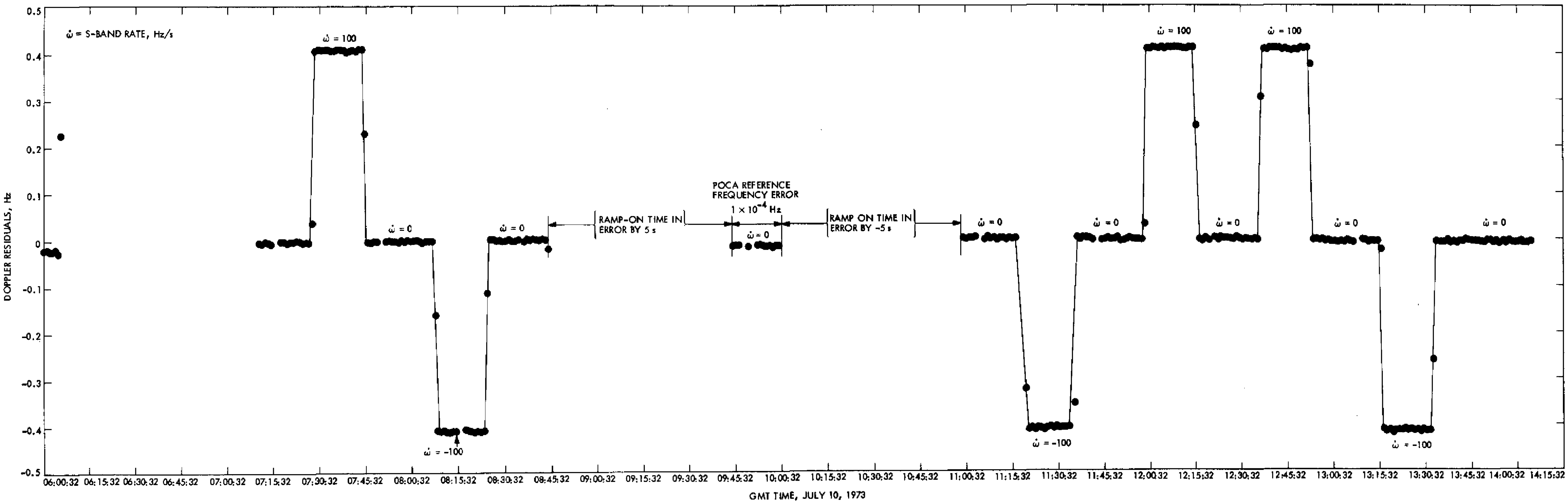

Fig. 3. Tora experiment, July 10, 1973—DSN 14 Pioneer 10 data with orbit and ramp corrections, second iteration.

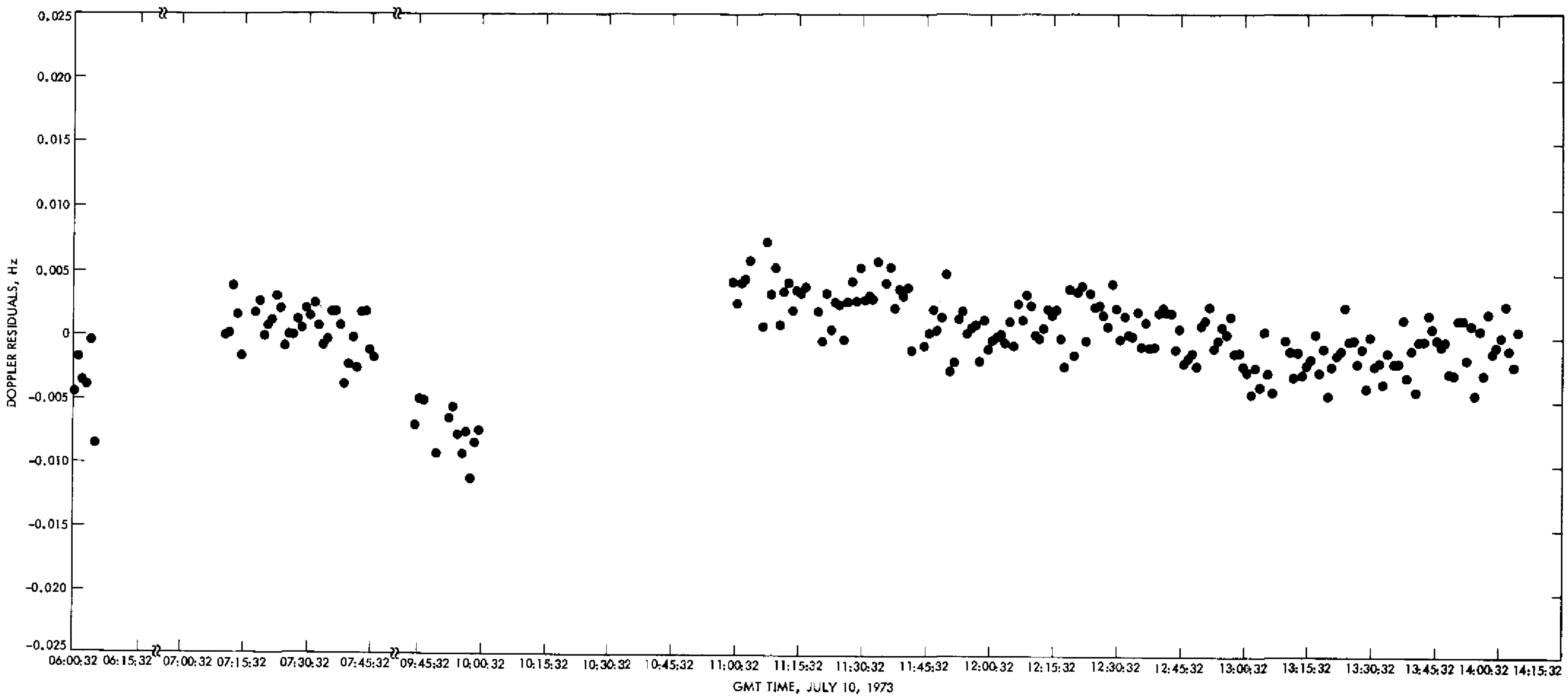

Fig. 4. Tora experiment, July 10, 1973—DSN 14 Pioneer data with orbit and ramp corrections, final iteration.